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Kinematics of cart pushing and pulling under different loads and surface gradient conditions

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Abstract.
BACKGROUND: Manual material handling incidents are responsible for a large portion of lost work days annually. With the transition to e-commerce, cart pushing and pulling tasks have become more common.
OBJECTIVE: This research explored the effects of surface gradient and load on full body kinematics during cart pushing and pulling tasks.
METHODS: Ten participants were recruited to complete two sets of tasks. Participants performed cart pushing tasks on three surface gradients and three load masses and downhill cart pulling tasks on two surface gradients and three load masses while being recorded with an optical motion capture system. Full body, three-dimensional joint angles were calculated for each task, and peak angles of the major body joints were analyzed using general linear models to determine the effects of the dependent variables.
RESULTS: During the cart pushing tasks, increased load mass and surface gradient both caused a significant increase in the peak joint angles of most body joints with surface gradient having the larger effect. When cart pushing and pulling tasks were compared with 5° and 10° surface gradients and three load masses, cart pushing resulted in significantly higher joint angles.
CONCLUSION: During manual material handling tasks involving a cart, surface gradients and load masses should be minimized.

Keywords: Kinematics, pushing, pulling, cart, gradient

1. Background

According to the Bureau of Labor Statistics, musculoskeletal disorders (MSDs) among occupational groups whose routine work requires manual material handling (laborers, trunk drivers, delivery service drivers, etc.) constitute 12% of all MSD cases that require days away from work [1]. While lower back MSDs are most common, shoulder and neck MSDs contribute significantly to morbidity among various occupational groups and create a substantial burden in terms of health and economics [2–6]. Assembly jobs that required highly repetitive work with small loads previously dominated the workforce, but the introduction and growing popularity of e-commerce have made distribution center jobs, which often

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require transporting large loads, more common [7]. These tasks are often performed by pushing/pulling the load on some type of cart. In fact, it has been estimated that nearly half of the manual material handling tasks common at workplaces demand pushing/pulling [8].

Research by Chaffin has identified that overexertion and slipping/tripping incidents are the two primary health risks of occupational pushing/pulling tasks [9]. The association between work-related pushing/pulling exertions and MSDs of the lower back [10–20] and neck/shoulder region [10,11,21–24] are well-documented. Recent studies have evaluated static exertions during pushing/pulling [25–27], changes in the magnitude of hand forces during dynamic exertions [28–30], and the effects of pushing/pulling exertions on physiological parameters such as heart rate and oxygen uptake [31–34]. However, the effect of pushing/pulling task-related variables on body kinematics and the factors that influence the kinematics have not been explored.

In general, peak force exertion occurs somewhere near the middle of the range of motion of most joints and decreases at extreme angles. Force exertions at extreme angles require more muscle activation, which can increase fatigue and the risk of MSDs. Study of kinematics, especially peak joint angles, could determine if the joint remained at a safe level during cart pushing/pulling tasks, further facilitating task and workplace improvements to reduce the risk of injury. The primary objective of this research was to identify the effect that surface gradient and mass of the load have on the kinematics of the major body joints and segments during cart pushing and pulling tasks.

2. Methods

2.1. Approach

The effects of dynamic pushing/pulling tasks on whole-body kinematics were studied in a laboratory setting. Participants performed cart pushing/pulling at three surface gradient levels (0°, 5°, 10°) with three load masses (20 kg, 30 kg, 40 kg). Dynamic pushing/pulling tasks were captured with an eight-camera, marker-based optical motion capture system. The data collected by the motion capture system were used to create a full-body model and determine kinematics of the elbows, shoulders, hips, knees, ankles and pelvis.

2.2. Participants

Ten male participants with mean (sd) age, stature, and mass of 23.8 (1.9) years, 172.0 (4.4) cm, and 70.0 (6.3) kg, respectively, were recruited for this study. While previous research has found significant gender differences in physiological loading and force exertions [31], and postural differences are likely, resources were allocated with an emphasis on finding differences due to task-related variables. Potential participants were excluded if they had current or previous musculoskeletal complaints or had any physical disabilities or conditions that would affect their ability to perform the tasks. Additionally, the Physical Activity Readiness Questionnaire (PAR-Q, Canadian Society for Exercise Physiology) was used to screen potential participants for cardiac and other health problems (e.g., dizziness, chest pain, heart problems, etc.).

2.3. Equipment

Optical motion capture system – An optical motion capture system (Vicon Motion Systems, Oxford, UK) with eight infrared cameras (MX-Series) was used to record the dynamic pushing/pulling tasks.

Three-dimensional positions of 14 mm retro-reflective markers attached to anatomical landmarks on the participant were captured at a rate of 100 Hz. Vicon Nexus 1.7.1 software was used to capture and process the data. Plug-in Gait, a Conventional Gait Model add-on for Vicon Nexus, was used to calculate joint angles based on the marker positions.

Plug-in Gait full-body marker set – The Plug-in Gait add-on requires a specific marker set for accurate kinematic calculations [35]. The plug-in gait marker set relies on 36 retro-reflective markers located on specific anatomical landmarks.

Custom Platform – A walkway with adjustable gradient was developed by first creating a 0.9 m wide $\times$ 3.7 m long wooden platform. The platform was attached to a 1.2 m $\times$ 1.8 m hydraulic scissor lift with hinges to allow the gradient to be adjusted. The platform was reinforced by two 10 cm $\times$ 10 cm pieces of lumber that ran the length of the platform. When elevated, the center of the platform was supported by two small hydraulic bottle jacks for extra stability.

Hand cart – A two-wheeled Harper 2-in-1 convertible hand truck (CSLEDTK1935P, Harper Trucks, Inc., Wichita, KS, USA) was used in this research. This is a standard hand cart that is commonly used to transport loads in an occupational setting. The hand cart has a mass of 14.3 kg and has a capacity of 317.5 kg with dimensions 1.25 m height, 0.31 m depth, and 0.33 m width.

2.4. Data collection

Upon arrival, the participants were familiarized with the experimental setup, procedures, and equipment and consent was obtained using a form approved by the local Institutional Review Board. To accurately track the body segments, the retro-reflective markers must follow the anatomical landmark on which they were placed. Therefore, the participant changed into spandex shorts and removed their shirt for the duration of the data collection. Anthropometric measurements and a short ($<$ 5 seconds) static capture with the subject standing in a T-pose were collected. Subsequently, the pushing/pulling tasks were completed.

Individual participants performed two experimental sessions. In the first session, the cart pushing task was performed on a flat walking surface (Fig. 1(a)). The participant tilted the cart backward and pushed the cart along the walkway using both hands. In the second session, pushing and pulling tasks were performed on walkways set at gradients of 5° and 10° from the horizontal. The pushing task required the participant to push the cart up the gradient (Fig. 1(b)). The pulling tasks required the participant to move the cart down the gradient in a controlled manner with both hands (Fig. 1(c)). For both sessions, three loads (20 kg, 30 kg, and 40 kg) were used.

Most participants faced a lot of difficulty pushing loads greater than 40 kg on the 10° walkway, therefore three loads of 20 kg (low), 30 kg (medium) and 40 kg (high) were selected in this study. In the industrial setting, ramps of different gradients are used based on the location and space constraints. Ramps of 0°, 2°, 5°, 8°, and 12° were tested in previous studies [30,36,37]. The two gradients of 0° and 5° were selected to be comparable with the previous studies, while the third gradient of 10° was determined based on the capture volume restriction of the optical motion analysis system used in this study.

2.5. Statistical analysis

In this study the effect of load mass, walkway gradient and direction of force application on whole-body kinematics were studied. The peak angles of the following were treated as the dependent variables: 1) Hip flexion, 2) Knee flexion, 3) Ankle flexion, 4) Elbow flexion, 5–7) Shoulder flexion, abduction, and

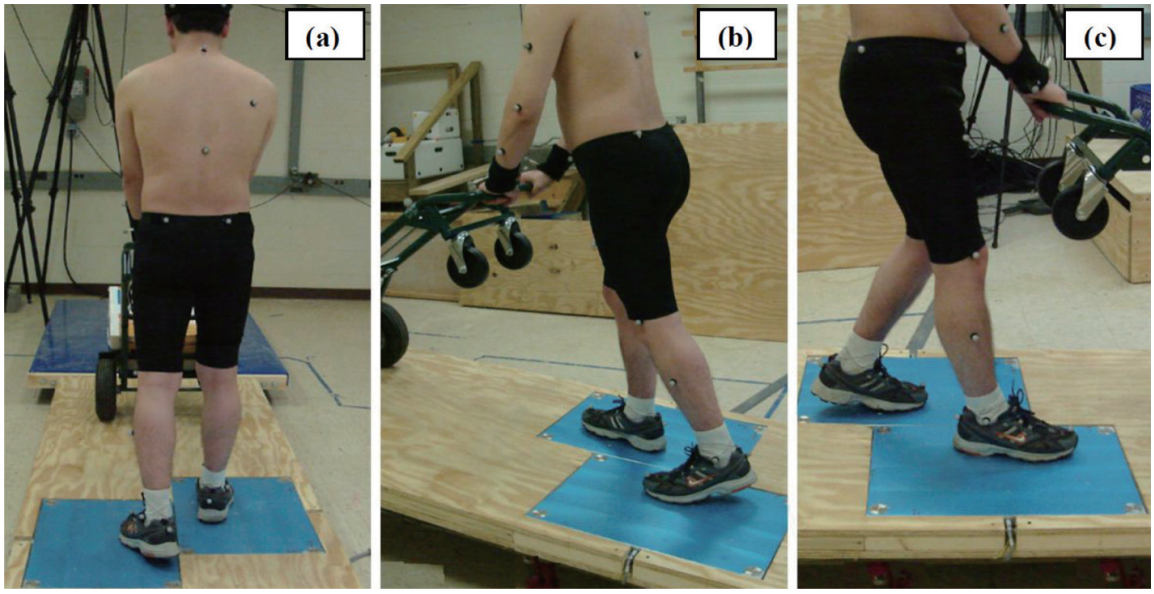

Fig. 1. Participant performing cart pushing/pulling tasks along (a) a flat walkway, (b) a ramped walkway while going uphill, and (c) a ramped walkway while going downhill. (Colours are visible in the online version of the article; http://dx.doi.org/10.3233/OER-130208)

rotation, 8–10) Trunk flexion, lateral bending, and rotation. Two General Linear ANOVA models were used to analyze the main effects and interaction effects of the independent variables on the dependent variables. In the first model load mass and gradients were treated as the fixed factors. Both load mass (20 kg, 30 kg, and 40 kg) and gradients (0°, 5°, 10°) were treated at three levels. In the second model, load mass, gradients, and direction of force application were treated as the fixed factors. The load mass was treated at three fixed levels (20 kg, 30 kg, and 40 kg), gradients was treated at two fixed levels (5°, 10°) and direction of force application was treated at two levels (pushing and pulling). In both models, participant was treated as a random variable. Minitab 16 statistical analysis software (Minitab Inc., PA, USA) was used to perform the analysis. From the ANOVA menu general linear model was selected to run the analysis. The adequacy of the linear model was evaluated by constructing a normal probability plot of the residuals between the actual and fitted values. For all the dependent variables, this graph was almost a straight line indicating that linear models were adequate for this study.

3. Results

3.1. Effect of load mass and gradient during pushing (model I)

In Model I, gradient and load mass both had a significant effect on several peak joint angles (Table 1). All peak joint angles were significantly affected by the change in gradient ($P < 0.001$) of the walkway, except for rotation of the trunk ($P = 0.207$). In general, peak joint angles increased as gradient increased, with the largest effect on hip flexion, ankle flexion, shoulder flexion, elbow flexion, and thorax flexion, causing peak joint angles to increase over 15° with a change from no gradient to 10° gradient. However, we also noted a significant decrease in the internal rotation of the shoulders (11.9°) with the same increase of gradient. Other differences in peak joint angles due to changes in gradient, while significant, were less than 10°.

Table 1
Main effects of load mass and gradient on body kinematics in Model I. Values are in Degrees (mean (SD))

Joint motion	Load mass (kg)				Gradient (°)			
	20	30	40	P	0	5	10	P
Hip flex.	39.5(15.2)	41.5(14.1)	43.6(16.8)	*0.001*	25.5(6.34)	43.2(8.75)	55.9(11.1)	*0.000*
Knee flex.	60.5(8.23)	62.1(7.82)	63.6(8.72)	*0.037*	58.1(7.56)	61.5(7.21)	66.5(7.96)	*0.000*
Ankle flex.	20.8(10.7)	23.1(10.1)	24.2(10.6)	*0.027*	14.6(7.07)	22.7(8.92)	30.8(8.64)	*0.000*
Shoulder flex.	30.5(11.9)	30.6(14.6)	33.8(21.4)	0.330	19.3(5.87)	37.5(13.2)	36.0(19.5)	*0.000*
Shoulder abd.	16.0(6.67)	19.1(6.38)	21.7(11.5)	*0.000*	15.3(4.90)	18.0(7.14)	23.3(11.1)	*0.000*
Shoulder rot.	36.6(9.71)	38.0(9.64)	36.3(10.4)	0.539	43.7(7.37)	35.3(9.48)	31.8(8.82)	*0.000*
Elbow flex.	66.0(14.7)	69.8(16.9)	70.2(18.6)	*0.038*	60.4(10.9)	62.9(11.5)	82.6(17.4)	*0.000*
Trunk flex.	20.7(10.3)	23.8(11.1)	26.7(14.2)	*0.000*	11.6(3.74)	26.0(9.15)	33.6(9.71)	*0.000*
Trunk abd.	3.92(2.17)	4.22(2.64)	4.53(2.78)	0.279	3.25(1.99)	4.19(2.43)	5.17(2.78)	*0.000*
Trunk rot.	5.99(3.11)	6.50(3.65)	6.22(3.86)	0.862	5.79(3.74)	5.95(3.55)	6.97(3.26)	0.207

Table 2
Main effects of load mass, gradient, and direction of force application on body kinematics in model II. Values are in Degrees (mean (SD))

Joint motion	Load mass (kg)				Gradient (°)			Direction of force		
	20	30	40	P	0	5	P	Push	Pull	P
Hip flex.	33.6(16.9)	36.1(15.9)	38.6(17.8)	*0.000*	31.9(13.9)	40.0(18.7)	*0.000*	22.5(8.19)	49.6(11.8)	*0.000*
Knee flex.	65.2(7.99)	67.5(7.79)	68.5(8.4)	*0.004*	64.3(7.73)	69.7(7.64)	*0.000*	70.0(7.22)	64.1(7.96)	*0.000*
Ankle flex.	20.1(7.57)	22.3(8.22)	23.6(9.51)	*0.000*	19.8(6.14)	24.1(9.90)	*0.000*	17.5(5.11)	26.5(8.96)	*0.000*
Shoulder flex.	28.4(11.1)	28.9(13.3)	32.2(19.3)	0.201	30.5(13.3)	29.1(16.3)	0.299	23.5(8.65)	36.0(17.1)	*0.000*
Shoulder abd.	14.0(7.34)	15.6(7.81)	17.6(12.0)	*0.005*	14.8(7.05)	16.6(11.0)	0.064	10.6(5.36)	20.7(9.72)	*0.000*
Shoulder rot.	36.0(9.62)	35.8(10.1)	35.3(10.3)	0.501	37.3(9.59)	34.2(10.1)	*0.002*	37.9(10.2)	33.5(9.28)	*0.000*
Elbow flex.	61.6(16.0)	63.8(18.4)	63.9(20.5)	0.175	58.6(12.5)	67.4(21.7)	*0.000*	53.3(12.9)	72.9(17.7)	*0.000*
Trunk flex.	18.8(10.0)	21.4(11.2)	24.5(14.6)	*0.000*	19.3(11.3)	23.7(12.7)	*0.000*	13.2(7.64)	29.9(10.1)	*0.000*
Trunk abd.	3.33(2.40)	3.72(2.63)	3.68(2.85)	0.639	3.24(2.53)	3.90(2.69)	0.064	2.69(2.13)	4.46(2.78)	*0.000*
Trunk rot.	5.71(3.49)	5.97(3.36)	5.47(3.52)	0.523	5.62(3.33)	5.81(3.57)	0.760	5.03(3.31)	6.41(3.47)	*0.001*

The effect of load mass was less dramatic, but was found to be a significant factor in peak hip flexion, knee flexion, ankle flexion, elbow flexion, shoulder abduction, and trunk flexion. Load mass had the largest effect on peak hip flexion, shoulder abduction, and trunk flexion, resulting in an increase of over 4° with a load mass increase from 20 kg to 40 kg, while the remaining peak joint angles showed differences of less than 4°. In general, increasing the load mass resulted in an increase in peak joint angles.

3.2. Effect of load mass, gradient and direction of force application (model II)

In Model II, all three factors had a significant effect on many of the peak joint angles (Table 2). The effect of direction was significant on all peak angles ($P \leqslant 0.001$), with joint angles generally higher when pushing with the only exceptions being knee flexion (5.9° decrease) and shoulder rotation (4.4° decrease). The largest differences between pushing and pulling were peak hip flexion (27.1°), elbow flexion (19.6°), trunk flexion (16.7°), shoulder flexion (12.5°), and shoulder abduction (10.1°). The remaining differences were below 10°.

In this model, only two gradients were analyzed, resulting in fewer significant main effects. When increasing the gradient from 5° to 10° a significant effect was found on peak hip flexion, knee flexion, ankle flexion, shoulder rotation, elbow flexion, and trunk flexion. However, all differences were below 5° except elbow flexion (8.8°), hip flexion (8.1°), and knee flexion (5.4°).

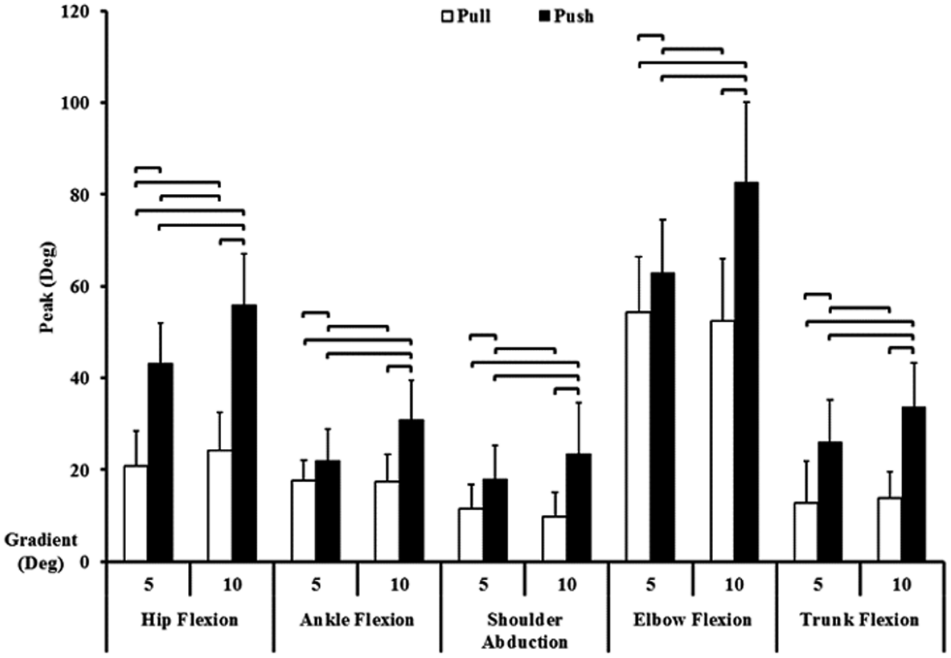

Fig. 2. Interaction effect of gradient and direction of force application on body kinematics. Brackets designate significantly different values.

The significant main effects of load mass in model I and model II were similar, except that the effect of load mass on peak elbow flexion in model II was not significant. With an increase from 20 kg to 40 kg, the only differences of 5° or more were found for peak hip flexion (5.0°) and trunk flexion (5.7°). The remaining differences were less than 5°.

Additionally, direction was found to have significant interactions with both load mass and gradient. The interaction between gradient and direction was significant for hip flexion, ankle flexion, shoulder abduction, elbow flexion, and trunk flexion. In general, when increasing the gradient from 5° to 10° a larger increase in peak angles was found when pushing than when pulling (Fig. 2). The interaction of load mass and direction was only significant for ankle flexion and shoulder abduction, however the effect was similar to the interaction between gradient and direction, with the peak angles increasing more during pushing than pulling as the load mass increased from 20 kg to 40 kg (Fig. 3).

4. Discussion

Manual carts are widely used in workplaces to transfer loads on surfaces with variable gradients. This study was aimed at quantifying kinematics of major body joints during bimanual cart pushing/pulling tasks performed under different walkway gradient and load conditions. The peak joint angles were used to compare the body postures across different task conditions. The posture of the upper body remained consistent throughout each task, therefore the peak angles are a good representation of the upper body posture throughout the tasks. The lower body was much more active.

The results of this study suggest that the direction of movement is the most important factor in body posture during cart pushing and pulling tasks, followed by the surface gradient and load mass. When

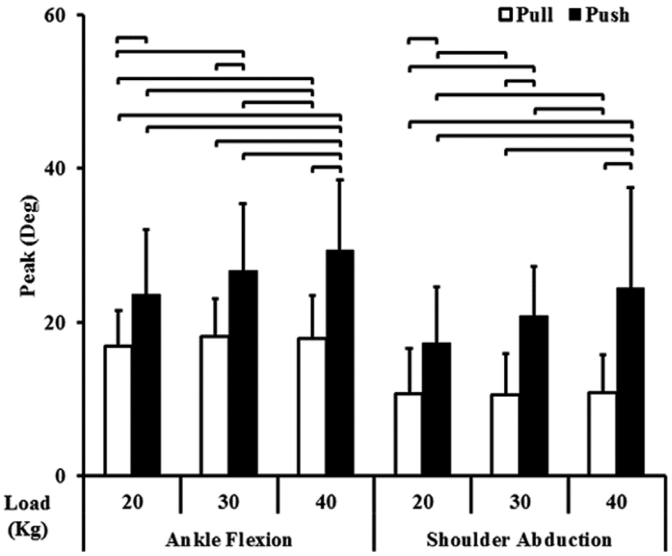

Fig. 3. Interaction effect of load mass and direction of force application on body kinematics. Brackets designate significantly different values.

pushing the cart uphill, the reaction force due to the mass of the cart is projected toward the participant's body, resulting in a more flexed posture. However, when the cart is being moved down the gradient, the reaction force due to the mass of the cart is projected away from the participant's body. Therefore, to control the load, the participant must maintain a more upright, rigid posture to counter-act the load of the cart.

The surface gradient was found to be a much more important factor than load mass on body kinematics during the cart pushing and pulling tasks. The largest effects of surface gradient were on the peak flexion of the hip, elbow, and trunk. Leroux et al. analyzed the effect of gradient on uphill and downhill walking on a treadmill, and found that knee, hip, and trunk flexion all showed a significant increase [38], which closely matches our results. The increased power generation was attributed to this observed change in kinematics of knee, hip, and trunk. The differences in peak elbow flexion observed in this study due to the increase in gradient are likely due to the alteration of the trunk posture. If the cart position is maintained and trunk flexion increases, the elbow angle will have to increase to compensate for the reduced distance between the cart and trunk.

The load mass had a minor effect on the peak joint angles. While several significant main effects of mass were found, the differences were generally minor. The interaction of mass and direction had a significant effect on ankle flexion and shoulder abduction. During the downhill pulling, joint angles tended to remain consistent with an increase in mass. However, increasing the load mass in the uphill pushing tasks generally caused an increase in the peak joint angles. The interaction effect between gradient and direction followed a similar trend across all peak angles. In general, angles remained consistent during the downhill pulling when increasing the gradient from 5° to 10° but a corresponding gradient change during uphill pushing caused an increase in most peak joint angles. During the downhill pulling, a rigid, upright posture was used to support the load, and that posture changed little with a change in mass and gradient. However, during the uphill pushing, less upright forward flexed body postures were used. These postures are less stable compared to the posture used during the downhill pulling and therefore affected more by the task demands due to the increased gradient and load.

Musculoskeletal disorders of the shoulder and lower back are commonly associated with work-related pushing and pulling exertions [11,20]. Direction of force application and surface gradient seems to affect the posture of shoulder and trunk joints during cart handling tasks. More flexed and abducted shoulder postures were observed during uphill pushing tasks performed on surfaces with increasing gradients. For the trunk, increased forward flexion was observed during similar conditions. Pushing exertions performed using flexed and abducted shoulder posture significantly increases the biomechanical loading of shoulder complex joints [39]. Similarly, forceful exertions performed using forward flexed posture also contributes to the increased loading of the low back joint [39]. Altogether, the direction of force application and the surface gradients appear to be the important task factors which may influence the risk of injuries during cart handling tasks.

There are a few limitations of this study that need to be acknowledged. First, the participants in this study were all male graduate students in engineering-related fields with little or no manual material handling experience. Second, the cart handling tasks were studied using a wooden walkway. At workplaces the workers operate on different types of surfaces, which may be different from the wooden surface used in this study. These surfaces may provide different levels of resistance against the movement of the cart and may affect the overall technique and working postures differently. Moreover, only one type of cart was tested in this study. Multiple types of carts are used for material handling in workplaces. The cart dimensions, especially handle height and physical dimensions with respect to its center of mass could affect the handling and posture. Future studies should look at larger, more diverse working conditions characterized by different work-surfaces, cart designs, and working populations of both genders to further improve our understanding of risk factors during cart handling tasks. Additionally, other metrics with a better established relationship with MSD risk, such as electromyography, should be collected.

5. Conclusions

This study looked at factors influencing posture during material handling tasks performed with a handcart. More stressful postures were observed during uphill pushing tasks compared to the downhill pulling tasks. The postural stress also increased with the increase in the surface gradient and mass of the load. However, the effect of surface gradient was found to be more pronounced than mass of the load on the postural changes during the cart pushing pulling tasks.

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